DuraMAT webinar (updated from, includes NIST/UL workshop)
Monday, 2022/1/10, 13:00 MT

"BACKFLIP: A Comparison of Emerging Non-Fluoropolymer-Based, Co-Extruded PV Backsheets to Industry-Benchmark Technologies"

Comparison of market-benchmark BACKsheet technologies to novel non-FLuoro-based co-extruded materials and their correlation and ImPact on PV module degradation rates (BACKFLIP)

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Present, Future, and Technical Project Motivations

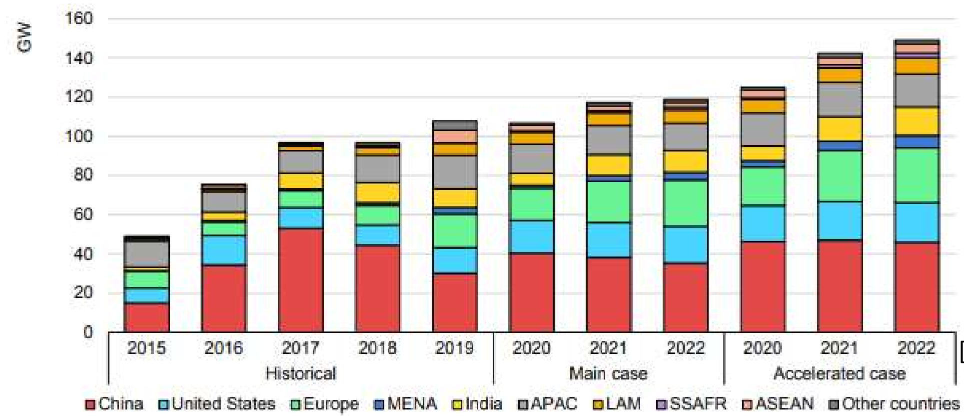
Historically, most backsheets made with **laminated PET core.**
Co-extruded polyolefin materials explored here.
-Pros: lower manufacture cost, simplifies RTI (no adhesives).
-Con: may facilitate through-thickness cracking.
-Unknown: durability of new materials.

Country **regulations may require fluorine-free backsheets**:
-Contain **no toxic materials.**
-**Preserve** raw **resources.**
-Recyclable, lower carbon footprint.

•**What to measure**, how?
-Critical characteristics and their correlation not fully established.
•**How to *age***?
-Connection between accelerated tests and field not established.

~340 Million Solar Panels!!!

Growth of global PV capacity (GW) | 2015-2022



[1]

[1] "Solar PV – Renewables 2020 – Analysis," *IEA*. https://www.iea.org/reports/renewables-2020/solar-pv (2021/4/13).

Look for in This Presentation

Connection between surface- and bulk-degradation is further compared, including:

- Surface morphology (microscopy) relative to surface roughness (gloss).

- Damage catalysis in MiMos vs. coupons (FTIR).

- Breakdown voltage in BS-6 (AAA) and other backsheets.

Recent references:
Thuis et. al., J PV, in press, https://doi.org/10.1109/JPHOTOV.2021.3117915.
Uličná, et. al., Proc Euro PVSEC Conf, 2021, 4CO.2.3

Materials and Test Conditions for the BACKFLIP Study

<u>Backsheets:</u>

- Benchmark (TPT, PPE, KPf).
- Known bad (AAA).
- Developmental (PO's, APO).

Arbitrary Index	Backsheet	Construction	Thickness [AVG±2 S.D.] (mm)	Comment
BS-1	PO-1	Coextruded	0.35±0.01	In Development
BS-2	PO-2	Coextruded	0.35±0.02	In Development
BS-3	TPT	Laminate	0.32±0.01	Traditional (reference)
BS-4	APO	Coextruded	0.35±0.01	Recently developed
BS-5	PPE	Laminate	0.36±0.01	Contemporary
BS-6	AAA	Coextruded	0.33±0.02	Known Bad
BS-7	KPf	Laminate	0.29±0.00	Contemporary

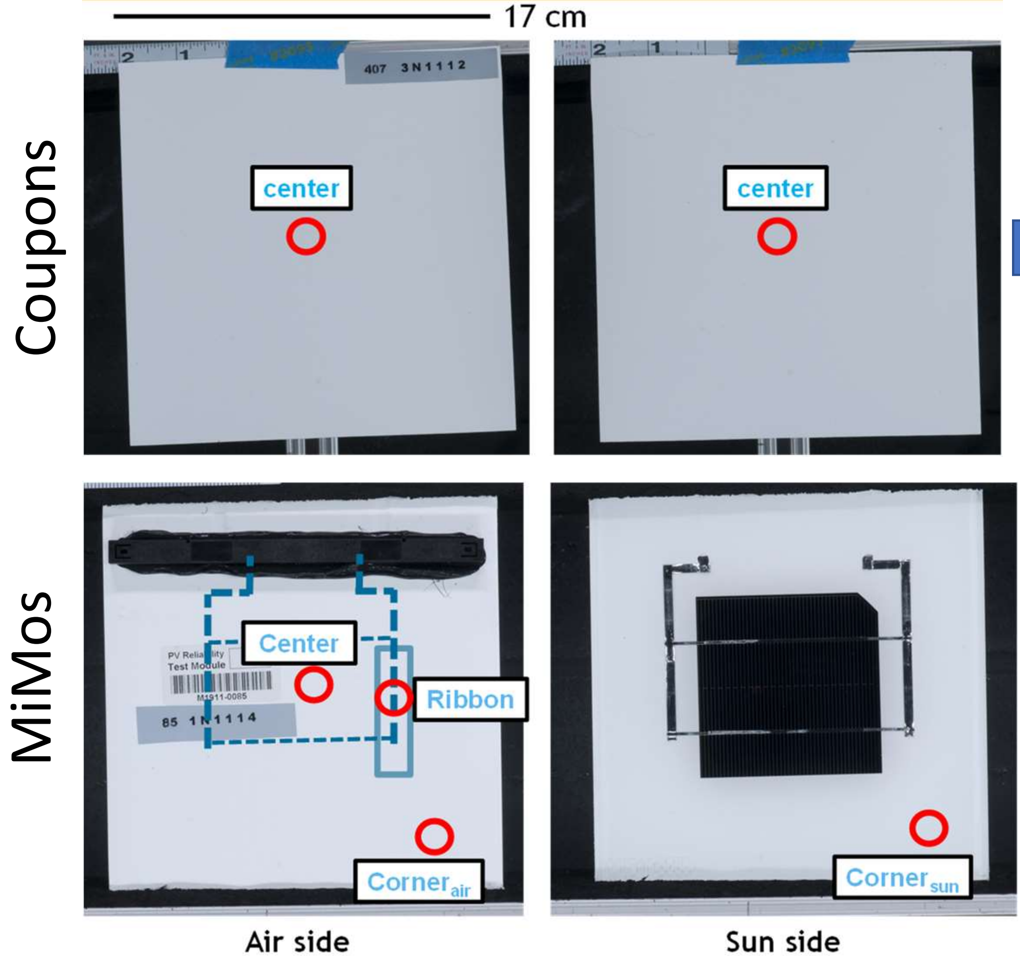
<u>Accelerated aging:</u>

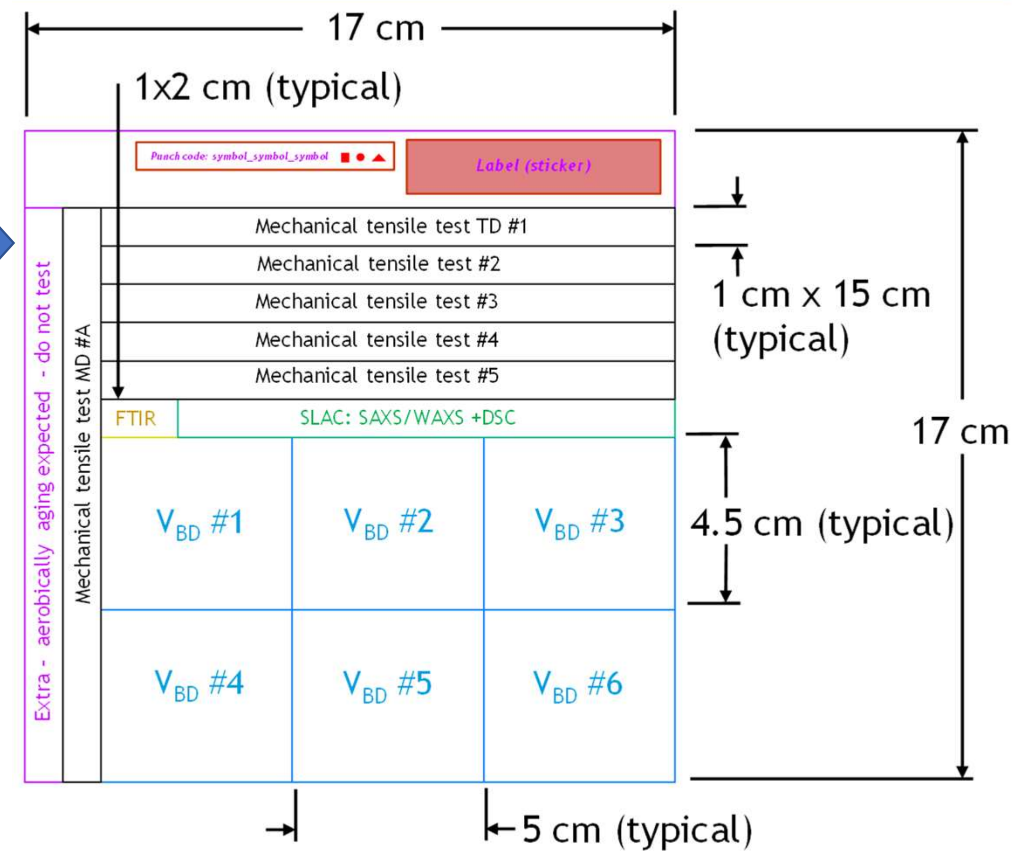
- Hygrometric (3x, including IEC 61215 "Damp Heat") → $E_{a,eff}$.
- UV weathering (2x, IEC TS 62788-7-2) → $E_{a,eff}$.
- UV weathering (2x, custom) → effect of H_2O spray.

Arbitrary Experiment Index	UV Irradiance ($W{\cdot}m^{-2}$ at 340 nm)	MiMo Temperature (°C)	Chamber Relative Humidity (%)	Water Spray?
1	0	85	85	N
2	0	65	85	N
3	0	45	85	N
a (A3)	0.8	69	20	N
b	0.55	59	20	N
c	0.55	62	~80%	Y
d (A2)	0.8	59	20	N

In Characterization

Specimens and Locations Characterized

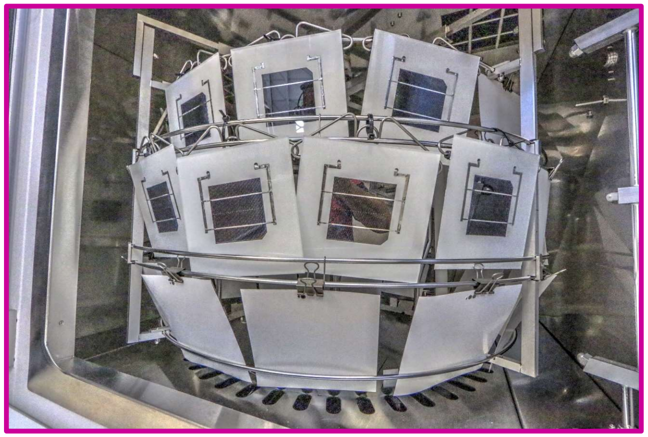




- Same 3 replicate MiMos through each experiment.
- 1 coupon·read point^{-1}·experiment^{-1} (destructive tests).

Accelerated Testing in the BACKFLIP Study

Coupon and MiMo specimens in Xe UV chamber (inside the carousel)



Coupon and MiMo specimens in Xe UV chamber (outside the carousel)

- **UV weathering** performed in high spectral fidelity Atlas "Weather-ometer" Xe lamp (ASTM D7869) chambers.

  17 cm MiMo size avoids shading between carousel rows.
  ⇒ ¼ cell MiMo's used at NREL.
  Removable cables, with j-box end caps.

- **Hygrometric aging** performed in separate dark chambers.

Coupon and MiMo specimens in hygrometric chamber

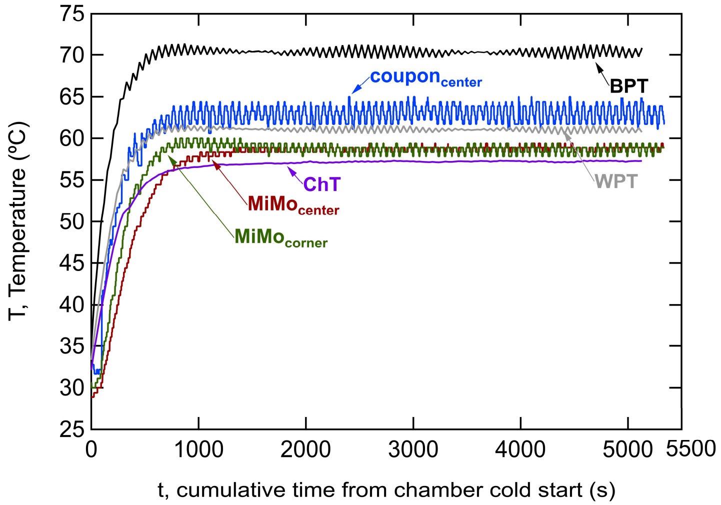
The Specimen Temperature Was Verified for UV Weathering

- Xe sources emit UV, VIS, and NIR light ⇒ heating above chamber temperature likely.
- MiMos and coupons may achieve different temperatures.

Kit from previous study, including wireless transmitters and their housing used here.

Takeaways:

- Specimen temperature stabilizes ~15-30 minutes.
- Minimal (1-2°C) difference center and corner.
  → *17 cm specimens still small.*
- Modest (up to 4°C) difference coupons and MiMos.
  → *Absorptance of cell, geometry + heat transfer.*
- Verified temperature will be used for Arrhenius analysis.



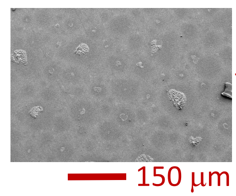
Temperature verification for "b" experiment.

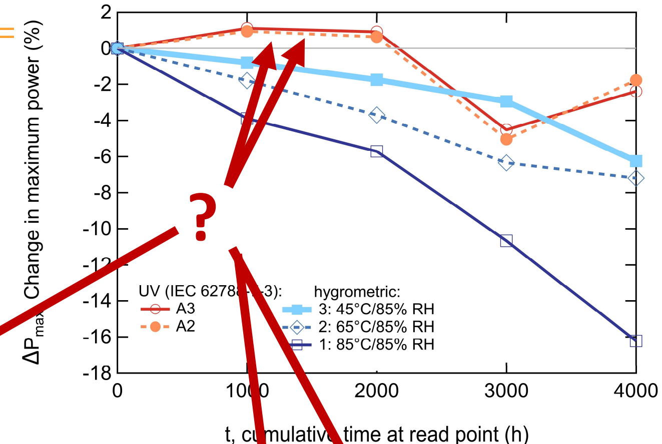
Grayness From EL Corroborates I-V Performance Change

- ΔP_{max}[MiMos] identified most damaging 85°C/85% RH experiment.
  Q: Can the degradation be verified, e.g. standardized EL images?

- *Imageio* and *NumPy* Python libraries can extract an average image grayness. Typically comparable (±<1%) of ImageJ.

Example: Sn-rich surface of soda-lime glass after A3 4000h.

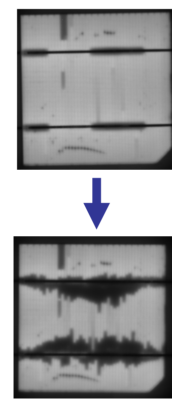




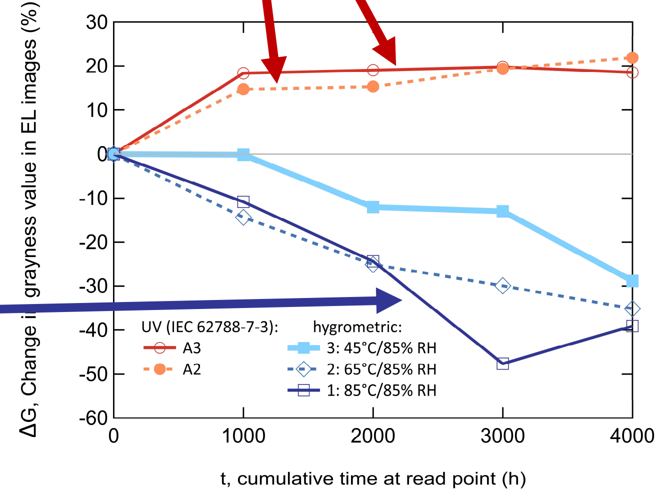
P_{max} evolution: AVG[all BS's] in first five experiments.

- ↓P_{max} in hygrometric aging quickly confirmed from grayness.

- ↑P_{max} in UV weathering also confirmed in grayness.
  May result from glass corrosion (AR effect).



BS-5 (PPE)

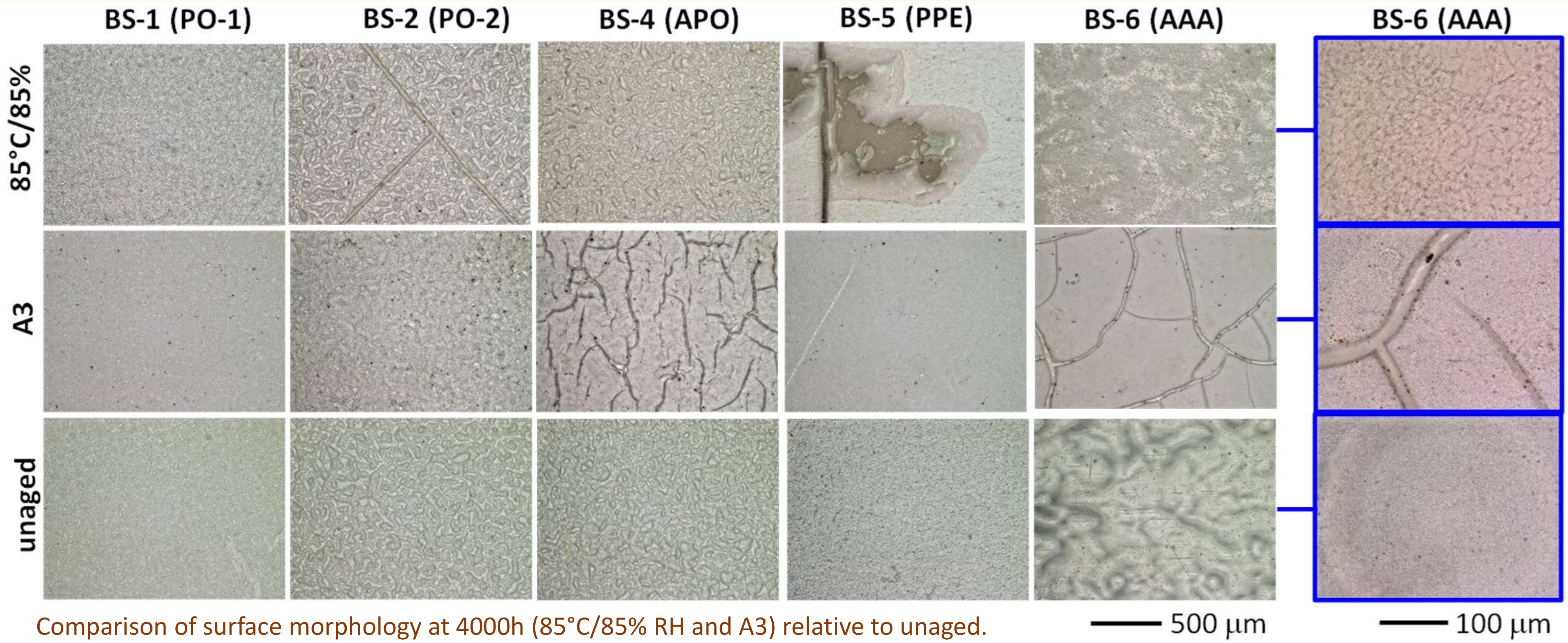


Grayness evolution: AVG[all BS's] in first five experiments.

- Presently working to verify I-V:EL fidelity using *pvimage* package to crop to cell only.

Q: What damage mode(s) might be affecting MiMo durability?

Surface Integrity of MiMo Air Side Surface From Optical Microscopy



Comparison of surface morphology at 4000h (85°C/85% RH and A3) relative to unaged.

- BS-4, BS-6: biaxial mud crack geometry presumably results from misfit strain.
- BS-6: smaller incipient micro-cracks in 85°C/85% RH.
- BS-5: micro-cracking and delamination in 85°C/85 % RH.

Changes in AVG[Gloss] BS-5, -6 Identified

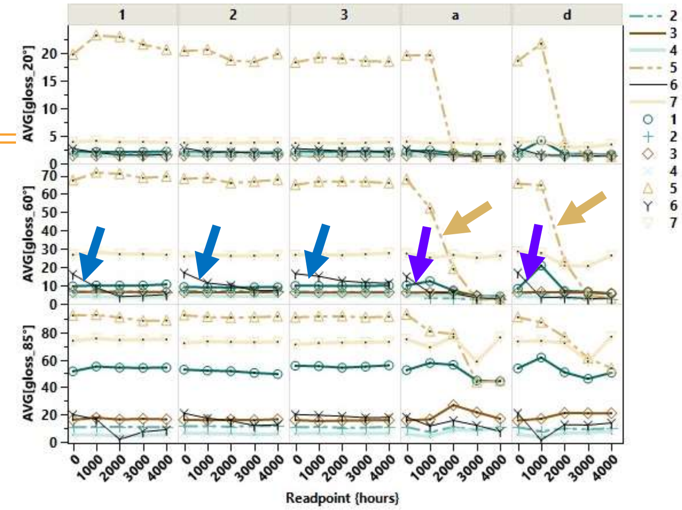
•Greatest initial gloss: BS-5, -7, then -1, e.g. 85°.

•Gloss reduced BS-5 (greatly), **-6** (slightly), at all incident angles in UV weathering, e.g., 60°.

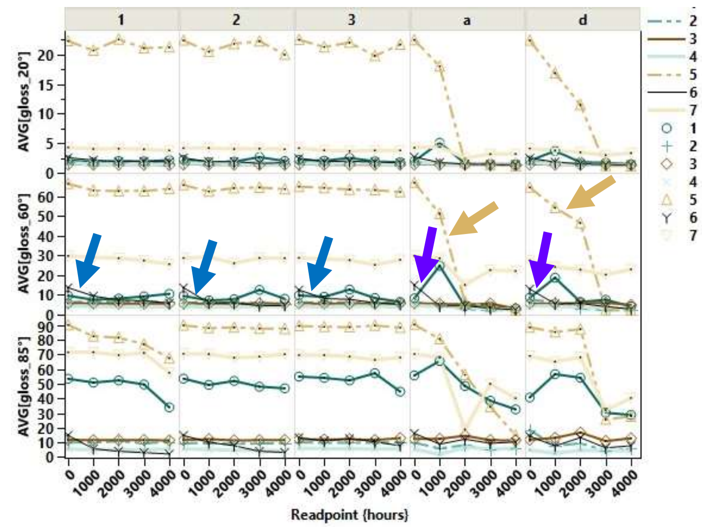
•Gloss reduced (slightly) **BS-6** throughout hygrometric aging, e.g., 60°.

•BS's with low gloss value remain low (may seem less affected), all experiments.

•Air side: similar trends observed between MiMos (center & corner) and coupons (center).



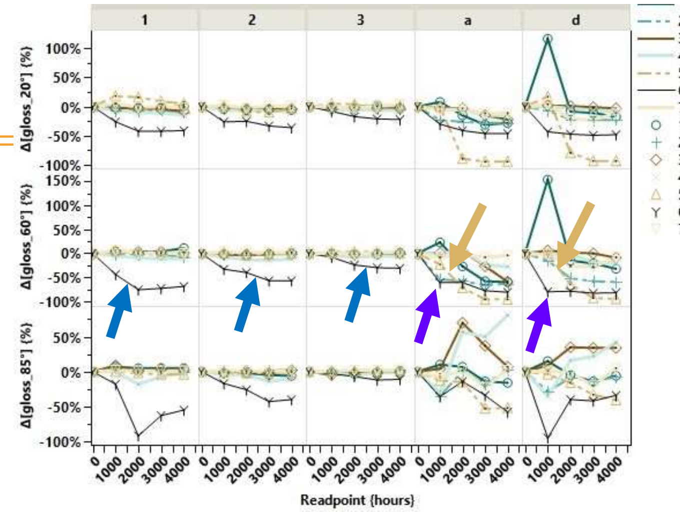
Comparison of AVG[gloss] at MiMo center for air side BS's through initial 5 experiments.



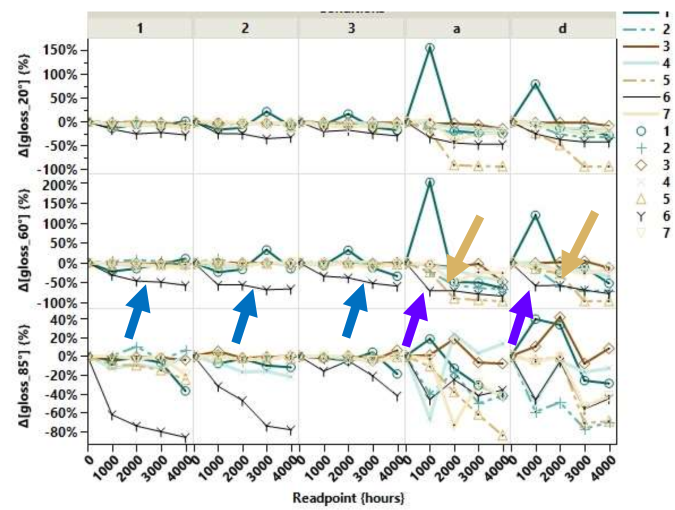
Comparison of AVG[gloss] at coupon center for air side BS's through initial 5 experiments.

Changes in Δ[Gloss] of Backsheets Identified

- Base values (AVG) distinguish the BS's; change (Δ) distinguishes their degradation.
- Gloss reduced BS-5, at all incident angles in UV weathering, e.g., 60°.
- Gloss reduced **BS-6** at all incident angles in UV weathering. Thermal activation observed through hygrometric aging, e.g., 60°.
- Other BS's also distinguished for Δ[gloss], e.g. in UV weathering.
- Spikes at read points observed, e.g. 1000 h. Compare MiMos and coupon results.



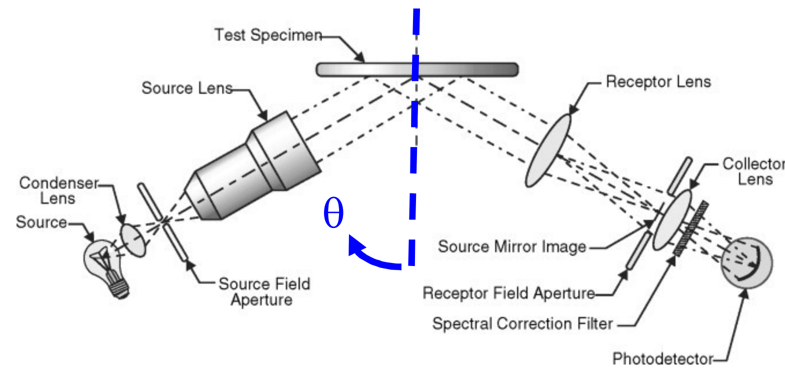
Comparison of Δ[gloss] at MiMo center for air side BS's through initial 5 experiments.



Comparison of Δ[gloss] at coupon center for air side BS's through initial 5 experiments.

Gloss Confirms Surface Roughening for Artificial Aging

- Gloss: 100 = polished glass reference; 0 = matte.
- Decrease in gloss indicates roughening of the surface, e.g., texturing, erosion, or cracking.
  - -Gloss immediately identifies BS-5.
    Not obvious in microscope. More than meets the eye?
  - -Gloss confirms BS-6 affected, both UV- and hygro-aging.



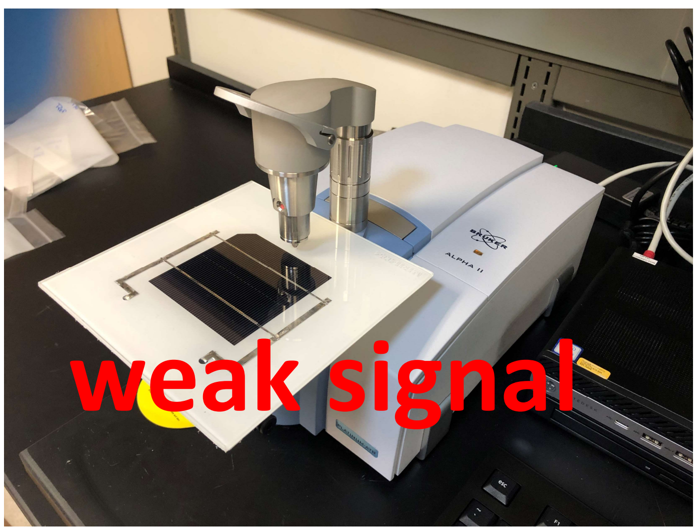
https://www.sciencedirect.com/topics/chemical-engineering/gloss-measurement

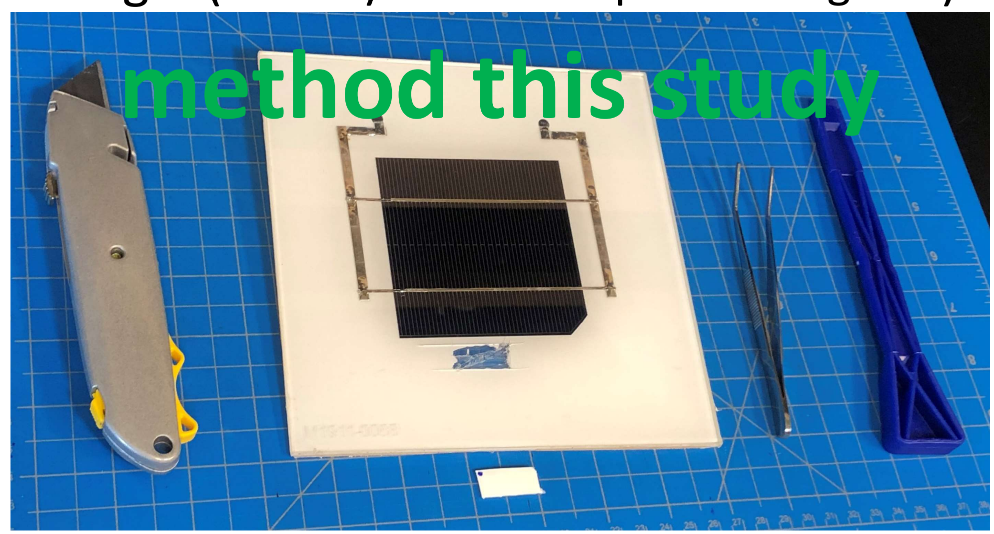
<u>Regarding gloss measurements</u>:

- Gloss might be another method to identify micro-scale cracking.
  - -Optimize λ and θ to feature size $\Rightarrow$ PV BS specific instrument & method.
    (Obtain a gloss scale that might identify BS-4 after UV).
- -Or- quantify surface roughness directly (profilometer, interferometer, etc).

Method of Comparing the Effect of Acetic Acid (MiMos vs. Coupons)

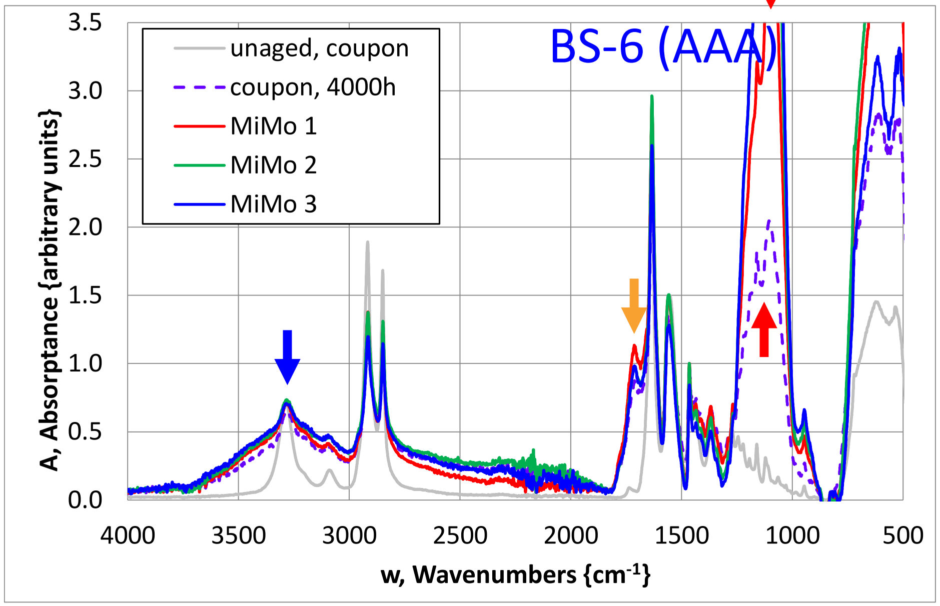
- Goal: verify adverse effects of acetic acid.
  (Possible catalyst that slowly escapes during aging.)
- Greatest concentration between cell and front glass.
  -Acid blocked from backsheet by cell. ☹
- Next most concentrated location: adjacent to cell. 😐
  -Double thickness EVA (source), far from MiMo edge. (Primary mass transport through BS).





- Compliant laminate → Extract 1 cm x 2 cm BS sample using box cutter.

Spectral Differences From FTIR of MiMos

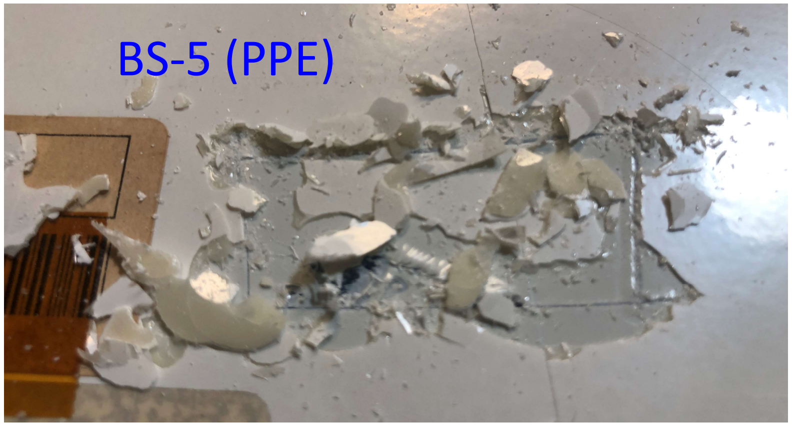


FTIR spectra for A2 UV weathering.

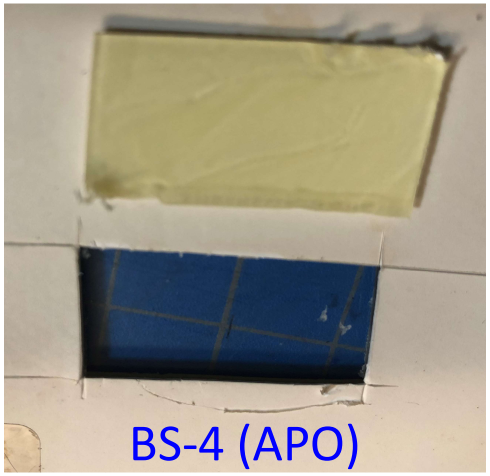
- Changes observed, both BS-6 coupons and MiMos:
  -3282, 2912 cm^{-1}. 1710 cm^{-1}. 1102 cm^{-1}.
- **Notable peak enhancement at 1102 cm^{-1}** for all replicate MiMos.
- Catalytic effect of acetic acid proposed:
  Lyu et. al., https://doi.org/10.1002/pip.3260.
- No other notable MiMo-specific differences observed, first 5 experiments.

Morphological Differences From FTIR of MiMos

•85°C/85%: core crumbled extracting PET BS's!
-Rank by damage: BS-5 (PPE) > BS-7 (KPf) > BS-3 (TPT).
-85°C/85%, c (H_2O spray): core *also* cracked for coupons.
-Preliminary result: c (H_2O spray) more destructive than 85°C/85%.
-*85 ℃/85% not field representative*
(often 2000h > 200y, doi: 10.1109/PVSC.2013.6744112).



MiMo specimen extraction site, 85°C/85% 4000h.



MiMo specimen extraction site, 85°C/85% 4000h.

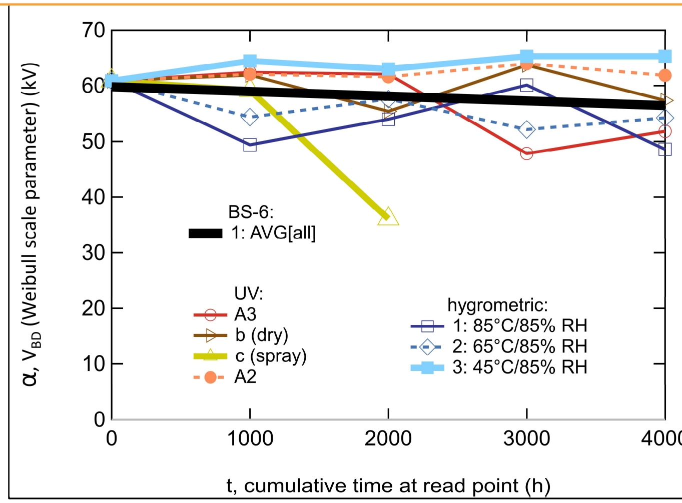
•BS-4 specimens readily extracted after 85°C/85%!
-(BS + EVA) readily removed from front glass.
-Not quantified, but suspect reduced interfacial adhesion.
-MiMo sun side discolored with subsequent photobleaching.
see: https://www.nrel.gov/docs/fy21osti/80362.pdf
-Will c (H_2O spray) be damaging like 85°C/85%?

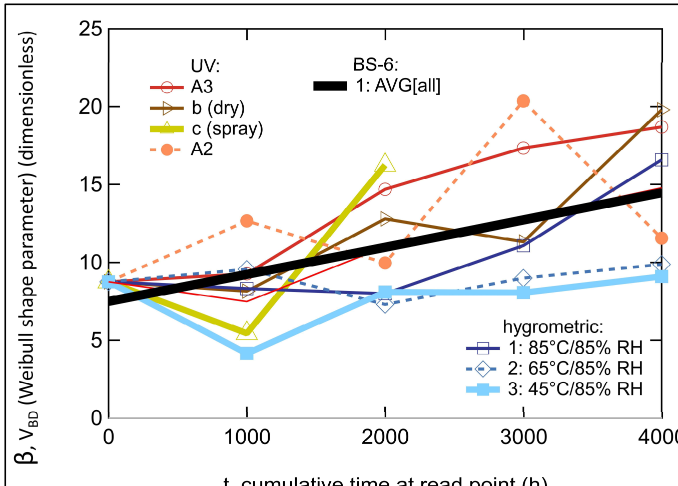
A Modest Effect of Aging Was Observed for V_{BD} of BS-6 (AAA)

- V_{BD} can only be consistently measured for BS-6, i.e. <100 kV.

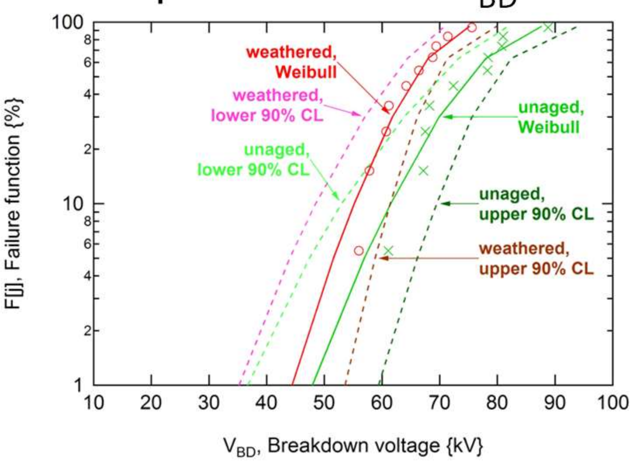
- Possible reduction of V_{BD} (α) with aging.
- Decrease in variability (β) with aging.

- A modest reduction in V_{BD} (α) was previously observed in the development of the V_{BD} test in IEC TS 62788-2.





Breakdown voltage (α, scale parameter) and variability (β, shape parameter) of BS-6 through the most affecting of first 5 experiments.



BS-6 (unaged and after A3 2000 h), from:
Miller et. al., SOLMAT, 2019,
https://doi.org/10.1016/j.solener.2019.01.092

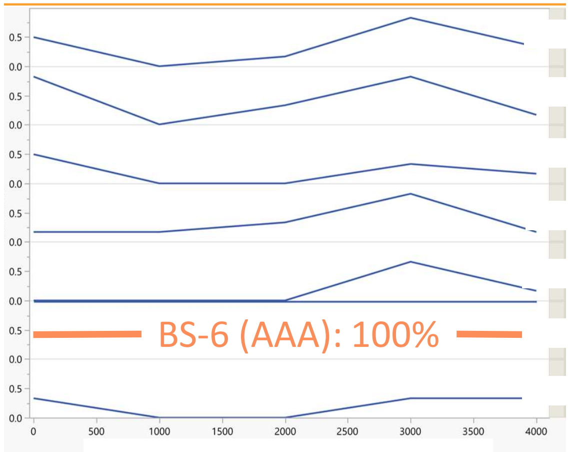
V_{BD} Suggests Bulk Damage in Hygrometric Aging

- Failure function, "F": 0% if all V_{BD} > 100 kV; 100% if all V_{BD} < 100 kV.

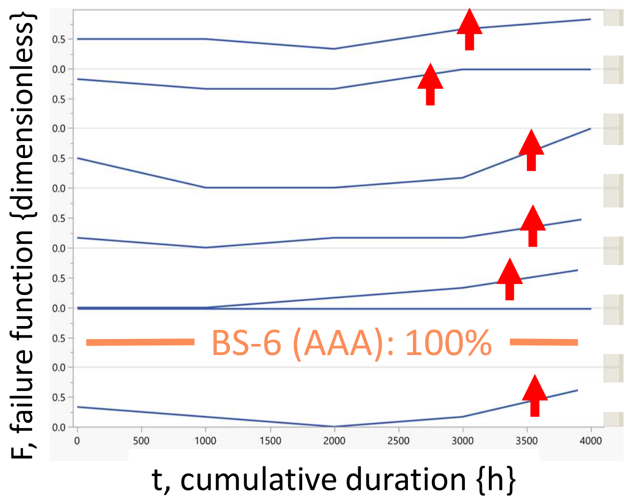
- No overt aging trend through UV weathering.
  - -BS-6 (AAA) always measurable.
  - -Surface (micro-cracking BS-4, BS-6; Δgloss BS-5, BS-6; FTIR BS-2,-4, -5,-6) vs. bulk (V_{BD} no Δ).

- F[remaining BS's] increased through hygrometric aging.
  - -Compare for t > 2000 h.
  - -Surface (micro-cracking BS-5, BS-6; Δgloss BS-6) vs. bulk (cutting BS-3, -4, -5, -7; V_{BD} all).

A3 UV weathering

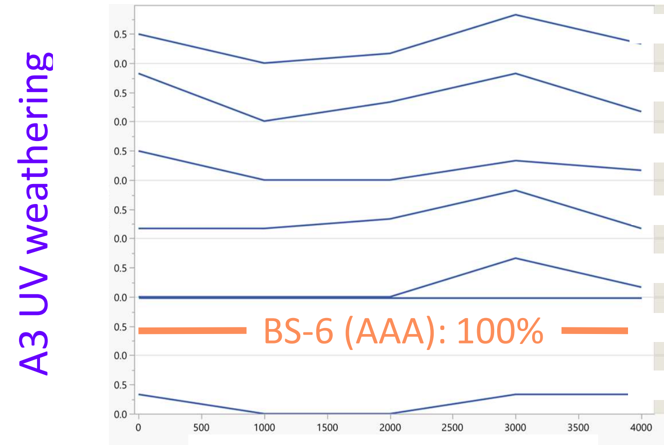


85°C/85% aging

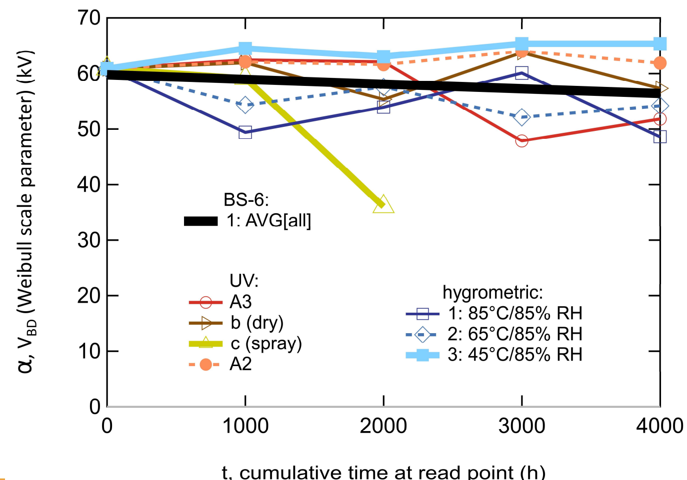


V_{BD}: Tailoring PV BS Performance; Verifying Surface & Bulk Connection

- V_{BD} > 100 kV suggests BS thickness could be reduced.
  - h_{BS} presently based on DTI (legacy h), not V_{BD} (verified performance).
  - Caution: effect of temperature or time not verified.



- Steady state aging invokes limited damage.
  - BS-6 (AAA) cracks in the field. Modest ΔV_{BD} here.
  - PPE (sun side) previously cracked from UV. Minimal ΔV_{BD} here.
  - Sequential- or combined-aging may better relate surface, bulk damage as well as identifying known-bads.



Remember from This Presentation

While verification of degradation is confirmed in additional characterizations, the connection between surface and bulk degradation remains limited:

- Gloss confirms surface roughening of PPE, AAA.
  -Standard equipment not optimized for PV BS's. Other methods exist besides Δgloss.

- Catalytic effect acetic acid confirmed from AAA MiMos.
- Greatly accelerated PET core damage for 85°C/85% on extraction of:
  BS-3 (TPT), BS-5 (PPE), BS-7 (KPf) MiMos. MQT 13, H_2O spray not field-based tests.

- Modest ΔV_{BD} observed through indoor aging of AAA.
- Other BS's: V_{BD} > 100 kV >> 8 kV $\rightarrow$ BS's thicker than needed.
- Minimal ΔV_{BD} steady state aging $\rightarrow$ more advanced-aging may help relate surface, bulk damage.

Acknowledgements

The authors would like to thank BACKFLIP contributors including:

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Note: DSM Advanced Solar B.V. is now Endurans Solar Solutions B.V.

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If you have interest in UV weathering, see PVQAT TG5, e.g. *https://www.pvqat.org/project-status/task-group-5.html*

The DuraMAT BACKFLIP Project Approach

NREL, Sandia, SLAC and Endurans partner to:

- 0. Understand role of backsheets on the longevity of modules and impact on energy yield.
- 2. Compare specimens: unaged,
  artificially-aged,
  outdoor-aged.
- 3. + 4. Evaluate relative rate of degradation of commercial and experimental backsheets.
- 4 + 5. Evaluate predictive parameters ($E_{a,eff}$). Identify and correlate characteristics, accelerated tests of concern.